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Abstract

North Cascade glacier annual balance measured on 10 glaciers from 1984–2006 yielded mean annual balance (ba) of –0.54 m/a, and –12.38 m cumulatively. This is a significant loss for glaciers that average 30–60 m in thickness, representing 20–40% of their entire volume. Two observed glaciers, Lewis Glacier and Spider Glacier, no longer exist.

The ba of North Cascade glaciers is reliably calculated based on 1 April snowpack water equivalent and ablation season temperature. 1 May forecasting of ba using the Pacific Decadal Oscillation and the Multivariate El Nino Southern Oscillation circulation indices correctly determined the sign of mass balance in 42 of 47 years. Glacier annual balance forecasting is an important step for summer water resource management in glacier runoff dominated stream systems. The forecast for North Cascade glaciers in 2007 is for a negative annual balance.

1 Introduction

Glaciers have been studied as sensitive indicators of climate for more than a century. Glacier behavior integrates water and energy balance factors to exhibit a maximum climate change signaling effect (IPCC, 1996). The North Cascades climate is known to be sensitive to inter-annual and decadal fluctuations in Pacific Basin climate (Walters and Meier, 1989; Hodge et al., 1998; Pelto and Hedlund, 2001; Bitz and Battisti, 1999). How reliably do North Cascade glaciers record climate? Can we forecast annual balance of North Cascade glaciers from atmospheric circulation indices of the Pacific Basin? This paper is the first step in approaching the problem of glacier mass balance forecasting. Many papers have focused on predicting glacier mass balance from climate records, but this has limited utility for water resource managers.

The North Cascade region contains more than 700 glaciers, which cover 250 km^2 and range in elevation from 1500–2500 m (Post et al., 1971). During the 1984–2006 period all 47 observed glaciers have been retreating (Pelto, 2006)

The importance of monitoring glacier mass balance was recognized during the International Geophysical Year in 1957. A series of benchmark glaciers around the world were chosen where mass balance would be monitored. This network has proven valuable, although coverage within any region is sparse. For example, there is just one benchmark glacier (South Cascade Glacier) in the lower 48 United States with ongoing measurements. Regional variation in glacier mass balance is due to variation in geographic characteristics such as aspect, elevation and location with respect to prevailing winds. No single glacier is representative of all others. Therefore, to understand the causes and nature of changes in glacier surface mass balance throughout a mountain range, it is necessary to monitor a significant number of glaciers (Fountain et al., 1991). The North Cascade Glacier Climate Project (NCGCP) was founded in 1983 to monitor glaciers throughout the range and identify the response of North Cascade Range, Washington glaciers to regional climate change. In 1983 the NCGCP selected for a long term annual balance monitoring 10 glaciers representing each part of the range and each type of glacier (Pelto, 1988). The glaciers represent a range of geographic conditions (Table 1). Annual balance has been continued on the 8 original glaciers that still exist, two have disappeared, Lewis and Spider Glacier. In 1990, Easton Glacier and Sholes Glacier were added to the annual balance program to offset the loss.

This paper focuses on data from this twenty-three year mass balance program and a 45 year record from the regional benchmark glacier, South Cascade Glacier monitored by the USGS (Krimmel, 2000).

2 Methods

Annual mass balance measurements are the most sensitive indicator of short-term glacier response to climate change. Annual mass balance is the difference between accumulation of snow and ice in winter and loss of snow and ice by ablation in summer. It is typically measured on a water year basis, beginning 1 October and ending 30

September.

NCGCP methods emphasize surface mass balance measurements with a relatively high density of sites on each glacier (<100 sites/km^2), consistent measurement methods, applied on fixed dates, and at fixed measurement locations (Pelto, 1996; Pelto and Riedel, 2001). Glaciers monitored in this program do not lose significant mass by calving or avalanching, thus changes observed are primarily a function of winter accumulation and summer ablation on the glacier's surface. The glaciers monitored also have relatively simple shapes and dynamics.

NCGCP essentially measures conditions on a glacier near the time of minimal mass balance at the end of the water year using a fixed date method. This is known as annual balance (Mayo et al., 1972; Pelto, 1997). Annual balance (ba) is defined as the change observed on a glacier's surface between successive balance minimums (Mayo et al., 1972). Measurements are made at the same time each year in July–August and again in late September near the end of the ablation season. Any additional ablation that occurs after the last visit to a glacier is measured during the subsequent hydrologic year. Annual balance can be calculated with this approach because winter and summer balance quantities, not measured prior to the NCGCP field season, cancel each other out (Pelto and Riedel, 2001).

Detailed descriptions of NCGCP methods have been documented in (Pelto, 1996, 1997, 2000; Pelto and Riedel, 2001). The use of a high measurement density and consistent methods provides that errors resulting from an imperfectly representative measurement network are largely consistent and correctable (Pelto, 2000).

3 Results and discussion

The cumulative balance trend, for the 10 NCGCP glaciers indicate an increasing trend of negative mass balance. The trend has become more negative and the interannual variation has increased. The mean annual balance from 1984 to 2006 on North Cascade glaciers is –0.54 m/a (Table 2). The cumulative balance is –12.38 m, equal to an ice thickness loss of at least 14 m (Fig. 2). Given a mean thickness of 30–60 m the mass loss is a 20–40% loss in total glacier volume. The increase in negative balance during a period of substantial retreat, suggests that the current retreat is insufficient for the glaciers to approach equilibrium. Glacier retreat during a period of fixed climate would increase mass balance as a glacier approached equilibrium.

Cross correlation of net mass balance and annual balance data from NCGCP and USGS programs support the comparison of the two data sets. Correlation coefficients between glaciers using the different field methods range from $r^2 = 0.79$ to 0.92 (Table 3). South Cascade Glacier has the largest negative balance, and has had the most significant retreat of this group in the last 20 years. The extensive retreat further indicates that its mass balance has been more negative.

Annual data from the eleven glaciers demonstrate the high degree of correlation each year (Fig. 3; Table 3). The linear trends overlap consistently enough that picking out an individual glaciers record is difficult in Fig. 2, indicating the similarity in sensitivity to annual climate conditions. There is a substantial annual range averaging +0.75 m in ba, however the trend from year to year is remarkably similar for all glaciers. Some years peculiarities occur that alter the annual balance of a particular glacier. For example a huge avalanche descended onto the Columbia Glacier in 2002 resulting in the highest annual balance of any glacier. In 2003, snowpack depths were below normal on all glaciers except above 2200 m on Easton Glacier, and it had the highest ba.

The loss in volume represents an extensive thinning, which has led to significant retreat of each glacier. This resulted in the final loss of Spider and Lewis Glacier. The Foss Glacier and Ice Worm Glacier have lost more than 30% of their total area since 1984 changing their character substantially, neither glacier will persist long with the current climate.

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4 Modeled versus measured annual balance

NCGCP has a temporally long enough glacier ba record to be contrasted meaningfully with climate data and climate indices. The two key climate parameters are ablation season temperature and accumulation season precipitation (Fig. 4). We examined ablation season temperature for five regional weather stations and for two different month combinations (May-September and June-September) and found the Diablo Dam record for June-September provides the best correlation. For accumulation season precipitation annual balance was correlated with precipitation at Diablo Dam and Concrete WA for differing combinations of months and with 1 April snow water equivalent (SWE) at five United States Department of Agriculture (USDA) Snowpack Telemetry stations (SNOTEL) stations; Rainy Pass, Lyman Lake, Stevens Pass, Miners Ridge and Fish Lake. The best correlation was with 1 April SWE. 1 April is near the snowpack maximum for most of the SNOTEL sites (Mote, 2003) In Fig. 4, 1 April SWE has declined by 25% at these stations since 1946, while winter season precipitation (November–March) has increased 1–3% at Concrete and at Diablo Dam, the most reliable long term weather stations. Mote (2003) in examining 40 stations in the Washington and British Columbia noted that substantial declines in SWE coincide with significant increases in temperature, and occur in spite of increases in precipitation. In Figs. 5 and 6 ba is plotted against ablation season temperature at Diablo Dam and 1 April SWE respectively. The resulting linear regression equations were then simply combined to calculate annual balance. The resulting equation requires as input only the mean June-September temperature at Diablo Dam (T) and the mean 1 April SWE (s) at the SNOTEL stations.

$$\mathrm{ba} = (2.5243s - 3.158) + (-0.772\,\mathrm{T} + 12.016) \quad (1)$$

Figure 7 has the calculated versus measured annual balance for the 8 North Cascade glaciers with ongoing records for the entire period. That a simple model such as this provides reasonable results indicates the close connection between the regional climate conditions and the mean annual balance of North Cascade glaciers.

5 Mass balance forecasting from climate indices

A number of papers have examined the relationship of Pacific Northwest glacier mass balance to atmospheric circulation indices (McCabe and Fountain, 1995; Hodge et al., 1998; Bitz and Battisti, 1999; Pelto and Miller, 2003). They have shown that these glaciers correlate with the Pacific Decadal Oscillation (PDO) and Multivariate El Nino Southern Oscillation Index (ENSO) particularly over a multi year period (McCabe and Fountain, 1995; Bitz and Batisti 1999; Hodge et al., 1998). Variations in the PDO and ENSO accounted for 35% and 20% of the variance in annual mass balance respectively of South Cascade Glacier (Bitz and Batisti 1999). The variances indicate the importance of each index, yet neither ENSO or PDO are well enough correlated with annual balance to provide any reasonable predictive or forecasting ability (Fig. 8) (Pelto and Miller, 2003).

The PDO Index is the leading principal component of North Pacific monthly sea surface temperature variability, poleward of 20 N (Mantua et al., 1997). During the positive PDO phase warm weather is favored in the Pacific along the northwest coast and over the Pacific Northwest. During the negative phase cool ocean water is found off the northwest coast and cooler temperatures across the Pacific Northwest (Mantua et al., 1997). In the past century: “cool” PDO regimes prevailed from 1890–1924 and again from 1947–1976, while “warm” PDO regimes dominated from 1925–1946 and from 1977 through the present (Mantua et al., 1997). It had been postulated in the late 1990’s that a negative PDO phase may have been starting, however we continue to have a dominantly positive PDO through 2006.

The El Niño/Southern Oscillation (ENSO) phenomenon is the most observable of the atmospheric circulation indices that lead to year-to-year climate variability. ENSO positive events (El Nino) herald abnormally warm sea surface temperatures (SST) over the eastern half of the equatorial Pacific. La Niña, is the opposite phenomenon, indicative of abnormally cold SST in the eastern half of the equatorial Pacific. ENSO is an east-west atmospheric pressure see-saw that directly affects tropical weather around the globe and indirectly impacts a much larger area (Wolter and Timlin, 1998). The ENSO multivariate index used here is based on the principal observed climate variables over the tropical Pacific. The index is a weighted average of the main ENSO features contained in the following six variables: sea-level pressure, the east-west and north-south components of the surface wind, SST, surface air temperature, and total amount of cloudiness (Wolter and Timlin, 1998). Sustained positive values of this ENSO index often indicate El Nino episodes. These positive values are usually accompanied by sustained warming of the central and eastern tropical Pacific Ocean. Negative values of this ENSO index are associated with stronger Pacific trade winds and warmer sea temperatures to the north of Australia (Wolter and Timlin, 1998).

The positive phase spatial patterns are very similar for both indices and it is postulated that they reinforce each other substantially when in phase (Gershunov et al., 1999). Both indices favor anomalously warm sea surface temperatures near the equator and along the coast of North America, and anomalously cool sea surface temperatures in the central North Pacific (Mantua et al., 1997; Gershunov et al., 1999).

Correlation of annual balance and PDO and ENSO atmospheric circulation indices was used to determine the utility for forecasting glacier mass balance from the PDO and ENSO (Pelto and Miller, 2003). Mass balance records from South Cascade Glacier (Krimmel, 2000) and NCGCP glaciers were used. The goal was forecasting mass balance as early as possible during the hydrologic year. Thus, various combinations of months were used. The best fit was for October–April for both indices. Table 4 displays the mean annual balance, and the October–April mean indices values. Each index is a critical indicator for annual balance that when taken alone does not predict specific annual balance values reliably (Fig. 8), but when considered together do provide an assessment of whether mass balance will be positive or negative. In much the same way that the seasonal forecast for the number of hurricanes is determined from a suite of indicators, this seems to be the most reasonable approach for glacier mass balance forecasting. Six forecasting rules are developed that can be applied to 47 possible years examined and provide a correct assessment in 42 of the 47 years.

- Rule 1. If both PDO and ENSO are positive, than glacier mass balance will be negative. This rule works in all 14 years it is applicable.
- Rule 2. If PDO is negative and ENSO is equilibrium or negative, mass balance will be equilibrium or positive. This rule is successful in 13 of 15 years.
- Rule 3. If PDO is positive and ENSO is neutral the glaciers will have an equilibrium or negative balance. The rule is correct in 4 of 5 years.
- Rule 4. If PDO is negative and ENSO is positive the glacier balance will be negative. This is true in 5 of 6 years
- Rule 5. If PDO is positive and ENSO is negative glacier mass balance will be negative. This rule provides an accurate result in 3 of 4 years.
- Rule 6. If PDO is neutral then glacier annual balance will be negative.

These rules provide us with the capability to forecast glacier annual balance given winter PDO and ENSO values. Given the neutral nature of the PDO and a positive ENSO value in the winter of 2007, it is forecast as of 1 May that North Cascade glacier annual balance will be negative in 2007.

6 Conclusions

Data from the USGS, and NCGCP glacier monitoring programs both indicate that the long-term trend for North Cascade glaciers continues to be strongly negative, despite a slightly positive trend for most glaciers from 1996–2000 (Fig. 3). The consistently high correlation coefficients between glaciers demonstrate the glaciers are responding to a regional climate change. There are no distinct regional variations within the range. The glaciers are in disequilibrium with the present climate as indicated by the mean annual balance loss of –0.54 m/a, a cumulative loss of –12.38 m, 20–40% of their entire volume and increasing negative balances despite retreat (Pelto, 2006)

Mean annual balance can be reliably calculated using ablation season temperatures from Diablo Dam and 1 April SWE from SNOTEL stations, for individual glaciers the error climbs appreciably. This indicates the strong connection between regional climate conditions and each glaciers annual balance.

Though the statistical and graphical relationship between annual balance and the PDO and ENSO climate indices is not quantitatively strong, both are a key influence of annual balance (Table 4). This is demonstrated being able to correctly forecast the sign of annual balance in 42 of 47 years simply by applying six forecasting rules using October-April PDO and ENSO indices values. As predictors of glacier mass balance El Nino events and warm phase PDO's favor negative balances and cool phase PDO's and La Nina's favor positive annual balances.

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Table 1. The geographic characteristics of the ten glaciers where annual balance is being monitored annually. Accumulation sources: wind drifting = WD, avalanche accumulation = AV, direct snowfall = DS.

GLACIER	ASPECT	AREA (km^2)	ACCUMULATION	TO DIVIDE	ELEVATION (m)
Columbia	SSE	0.9	DS, DW, AV	15 km west	1750–1450
Daniels	E	0.4	DS, WD	1 km east	2230–1970
Easton	SSE	2.9	DS	75 km west	2900–1700
Foss	NE	0.4	DS	At divide	2100–1840
Ice Worm	SE	0.1	DS, AV	1 km east	2100–1900
Lower Curtis	S	0.8	DS,WD	55 km west	1850–1460
Lynch	N	0.7	DS,WD	At divide	2200–1950
Rainbow	ENE	1.6	DS,AV	70 km west	2040–1310
Sholes	N	0.9	DS	70 km west	2070–1630
Yawning	N	0.3	DS	At divide	2100–1880

Table 2. The annual of the 10 North Cascade glaciers in this study by the NCGCP, and annual net balance for South Cascade Glacier from the USGS study (Krimmel, 2000).

Glacier	Columbia	Daniels	Easton	Foss	I. Worm	L Curtis	Lynch	Rainbow	Sholes	Yawning	SCascade
Year	NCGCP	NCGCP	NCGCP	NCGCP	NCGCP	NCGCP	NCGCP	NCGCP	NCGCP	NCGCP	USGS
1984	0.21	0.11		0.51	0.86	0.39	0.33	0.58		0.09	0.12
1985	-0.31	-0.51		-0.69	-0.75	-0.16	-0.22	0.04		-0.23	-1.20
1986	-0.20	-0.36		0.12	-0.45	-0.22	-0.07	0.20		-0.10	-0.61
1987	-0.63	-0.87		-0.38	-1.39	-0.56	-0.30	-0.26		-0.47	-2.06
1988	0.14	-0.15		0.23	-0.24	-0.06	0.17	0.43		-0.06	-1.34
1989	-0.09	-0.37		0.09	-0.67	-0.29	0.03	-0.24		-0.19	-0.91
1990	-0.06	-0.68	-0.58	-0.27	-0.92	-0.51	-0.12	-0.46	-0.32	-0.32	-0.11
1991	0.38	-0.07	0.41	0.30	0.63	0.04	0.36	0.44	0.48	0.23	0.07
1992	-1.85	-1.70	-1.67	-1.92	-2.23	-1.76	-1.38	-1.65	-1.88	-2.06	-2.01
1993	-0.90	-0.83	-1.01	-0.73	-1.02	-0.48	-0.62	-0.80	-0.96	-0.66	-1.23
1994	-0.96	-0.45	-0.92	-0.68	-1.23	-0.55	-0.40	-0.72	-0.88	-0.62	-1.60
1995	-0.45	0.24	-0.31	0.31	0.47	-0.21	0.18	-0.20	-0.25	-0.26	-0.69
1996	-0.62	0.45	0.22	0.34	0.57	-0.18	0.53	0.12	0.06	0.34	0.10
1997	0.35	0.88	0.53	0.50	0.76	0.27	0.62	0.51	0.42	0.50	0.63
1998	-1.46	-1.82	-1.87	-1.95	-1.64	-1.38	-1.97	-1.49	-1.56	-2.03	-1.60
1999	1.75	1.52	1.61	1.56	2.15	1.55	1.45	1.84	1.76	1.63	1.02
2000	0.40	-0.25	-0.10	-0.10	-0.33	-0.25	-0.24	0.15	-0.08	-0.18	0.38
2001	-1.52	-1.75	-1.93	-1.92	-2.15	-1.88	-1.82	-1.71	-1.83	-1.94	-1.57
2002	0.60	-0.18	0.18	0.10	0.05	0.13	-0.13	0.12	0.21	0.26	0.55
2003	-1.17	-1.52	-0.98	-1.35	-1.40	-1.25	-1.20	-0.98	-1.12	-1.85	-2.10
2004	-1.83	-2.13	-1.06	-1.94	-2.00	-1.51	-1.98	-1.67	-1.86	-1.78	-1.65
2005	-3.21	-2.90	-2.45	-3.12	-2.85	-2.75	-2.62	-2.65	-2.84	-3.02	-2.45
2006	-0.98	-1.25	-0.79	-1.02	-1.35	-1.06	-1.05	-0.61	-0.71	-0.93	

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Table 3. Cross Correlation of mass balance on North Cascade glaciers, range from 0.79–0.99.

	Colum-bia	Daniels	Easton	Foss	Ice Worm	Lower Curtis	Lynch	Rainbow	Sholes	Yawning
Daniels	0.90									
Easton	0.90	0.89								
Foss	0.94	0.97	0.93							
Ice Worm	0.89	0.95	0.93	0.94						
Lower Curtis	0.96	0.95	0.94	0.97	0.94					
Lynch	0.93	0.98	0.90	0.98	0.93	0.95				
Rainbow	0.96	0.94	0.95	0.97	0.98	0.98	0.96			
Sholes	0.94	0.96	0.94	0.98	0.97	0.98	0.97	0.97		
Yawning	0.97	0.95	0.94	0.98	0.97	0.98	0.96	0.99	0.98	
South Cascade	0.85	0.84	0.89	0.82	0.87	0.81	0.79	0.81	0.85	0.92

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Table 4. The mean value of winter PDOW (October-April) and winter ENSOW (October–April). Glacier mass balance from South Cascade Glacier 1960-1986, combined South Cascade and NCGCP data 1987–2005 (bn). The relative phase: positive, >0.2 (p), negative, <–0.2 (n) and equilibrium –0.2 to –0.2 (e), for PDOW, ENSOW indices and glacier annual balance. The number of the rule utilized from Sect. 6. Lastly if the rule correctly yields the annual balance in terms of negative, equilibrium or positive it is noted by a yes, if not a no.

Year	PDOW	ENSOW	bn	PDOW	ENSOW	bn	Rule#	Result
1960	0.34	–0.17	–0.5	p	e	n	3	yes
1961	0.30	–0.23	–1.1	p	n	n	5	yes
1962	–1.64	–0.79	0.2	n	n	p	2	yes
1963	–0.62	–0.71	–1.3	n	n	n	2	no
1964	–0.83	0.41	1.2	n	p	p	4	no
1965	–0.63	–0.64	–0.17	n	n	e	2	yes
1966	–0.42	1.06	–1.03	n	p	n	4	yes
1967	–0.73	–0.52	–0.63	n	n	n	2	no
1968	–0.54	–0.68	0.01	n	n	e	2	yes
1969	–0.74	0.54	–0.73	n	p	n	4	yes
1970	0.78	0.34	–1.2	p	p	n	1	yes
1971	–1.44	–1.38	0.6	n	n	p	2	yes
1972	–1.56	–0.74	1.43	n	n	p	2	yes
1973	–0.27	1.41	–1.04	n	p	n	4	yes
1974	–1.10	–1.70	1.02	n	n	p	2	yes
1975	–0.45	–0.85	–0.05	n	n	e	2	yes
1976	–1.40	–1.55	0.95	n	n	p	2	yes
1977	1.05	0.49	–1.3	p	p	n	1	yes
1978	0.34	0.81	–0.38	p	p	n	1	yes
1979	–0.16	0.29	–1.56	e	p	n	6	yes
1980	0.70	0.75	–1.02	p	p	n	1	yes
1981	0.87	0.15	–0.84	p	e	n	3	yes
1982	0.31	–0.07	0.08	p	e	e	3	yes
1983	0.87	2.68	–0.77	p	p	n	1	yes
1984	1.38	–0.07	0.12	p	e	p	3	no
1985	0.73	–0.45	–1.2	p	n	n	5	yes
1986	0.91	–0.15	–0.71	p	e	e	3	yes
1987	1.78	1.29	–2.56	p	p	n	1	yes
1988	1.23	0.98	–1.64	p	p	n	1	yes
1989	–0.52	–1.16	–0.71	n	n	n	2	yes
1990	–0.30	0.26	–0.73	n	p	n	4	yes
1991	–1.37	0.33	–0.2	n	e	p	2	yes
1992	0.40	1.61	–2.03	p	p	n	1	yes
1993	0.66	0.80	–1.23	p	p	n	1	yes
1994	1.05	0.52	–1.6	p	p	n	1	yes
1995	–0.50	0.99	–0.69	n	p	n	4	yes
1996	0.59	–0.48	0.1	p	n	e	5	yes
1997	0.28	–0.20	0.63	p	n	p	5	no
1998	1.30	2.46	–1.86	p	p	n	1	yes
1999	–0.58	–0.93	1.02	n	n	p	2	yes
2000	–1.16	–0.95	0.38	n	n	p	2	yes
2001	–0.04	–0.48	–1.57	e	n	n	6	yes
2002	–0.67	–0.05	0.55	n	e	p	2	yes
2003	1.51	0.91	–1.1	p	p	n	1	yes
2004	0.54	0.34	–1.7	p	p	n	1	yes
2005	0.39	0.65	–2.9	p	p	n	1	yes
2006	–.08	–0.43	–0.98	e	n	n	6	yes
2007	–.07	0.84		e	p	?	6	?

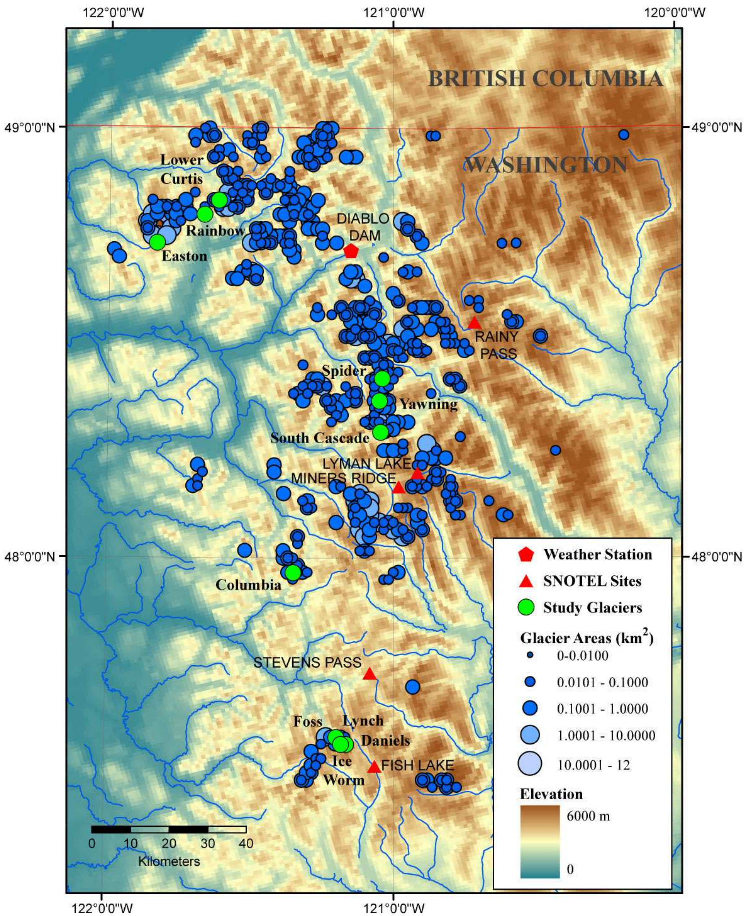

Fig. 1. Regional locator map showing glaciers discussed. C=Columbia, D=Daniels, E=Easton, F=Foss, IW=Ice Worm, L=Lynch, LC=Lower Curtis, R=Rainbow, SC=South Cascade, Y=Yawning

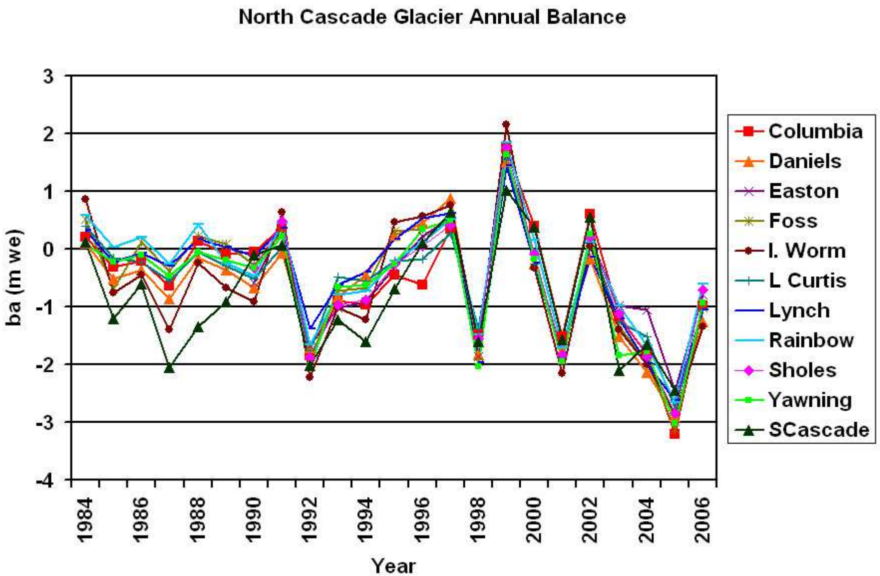

Fig. 2. The annual balance of North Cascade glaciers 1984–2006, records for individual glaciers are difficult to distinguish due to the consistently high correlation between glaciers.

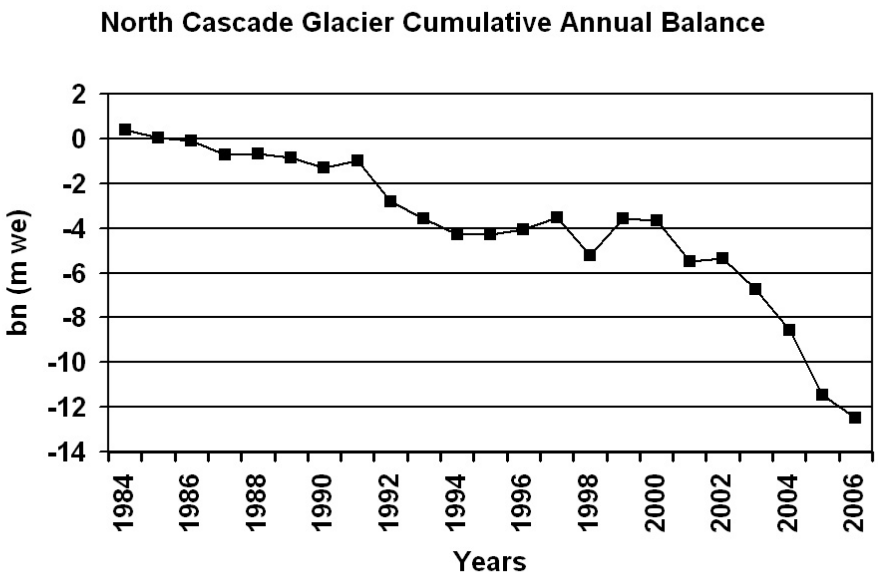

Fig. 3. Cumulative mass balance record of North Cascade glaciers, 1984–2006, in meters of water equivalent. The increasingly negative trend is evident.

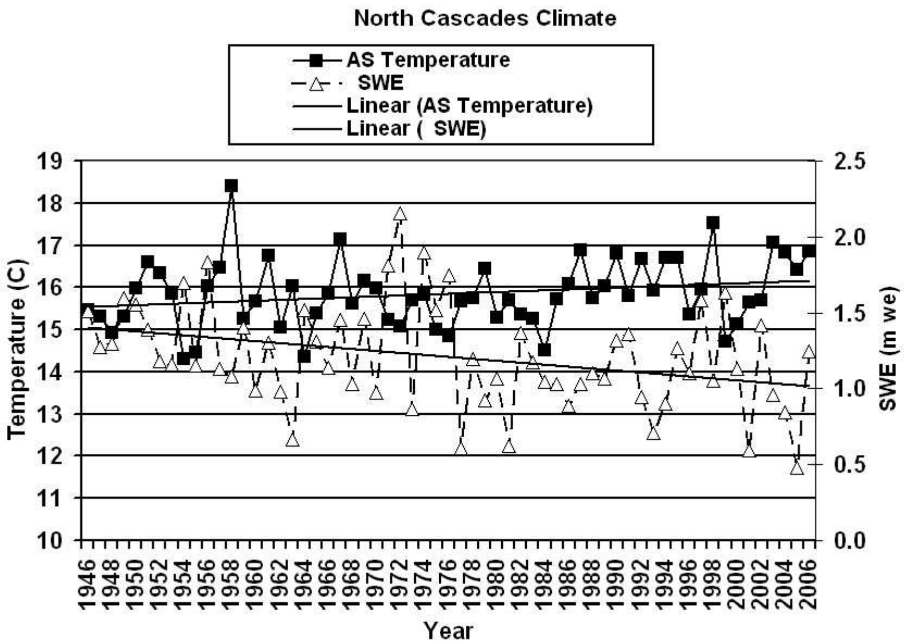

Fig. 4. 1 April SWE at five USDA Snotel stations and ablation season temperature (June-September) at Diablo Dam from 1946–2006. This illustrates the 0.6°C ablation season (June September) warming and 25%+ decline in 1 April SWE.

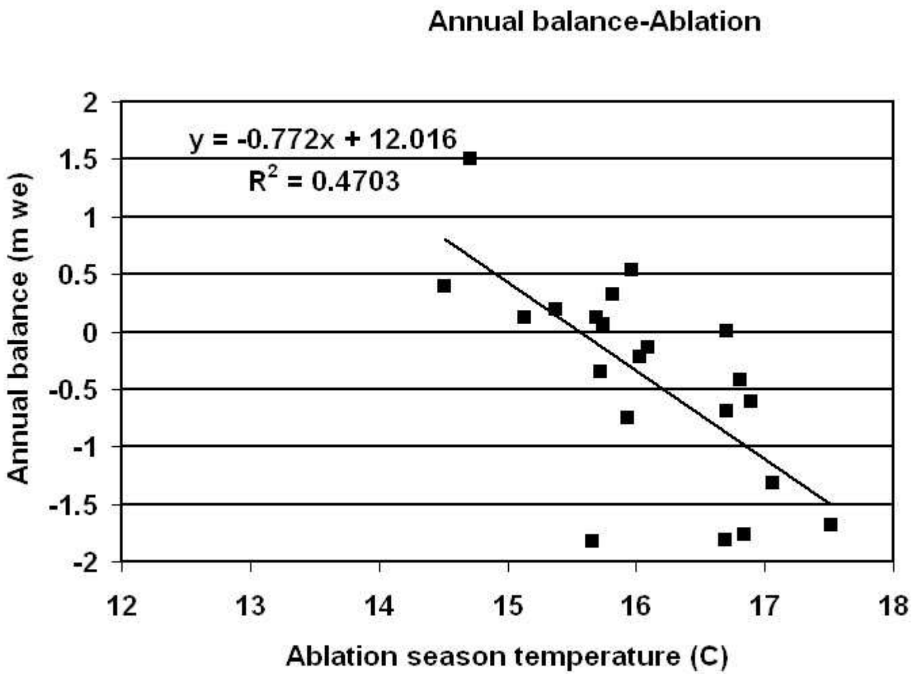

Fig. 5. Scatter plot and linear regression of ablation season temperature (June–September) at Diablo Dam and measured annual balance of North Cascade glaciers.

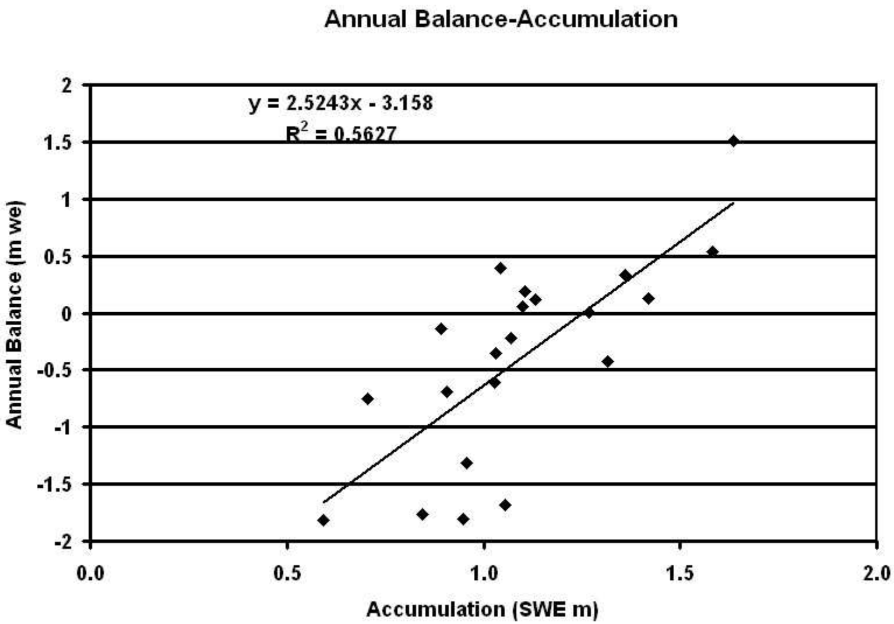

Fig. 6. Scatter plot and linear regression line between mean 1 April SWE at five USDA SNOTEL stations and measured annual balance of North Cascade glaciers.

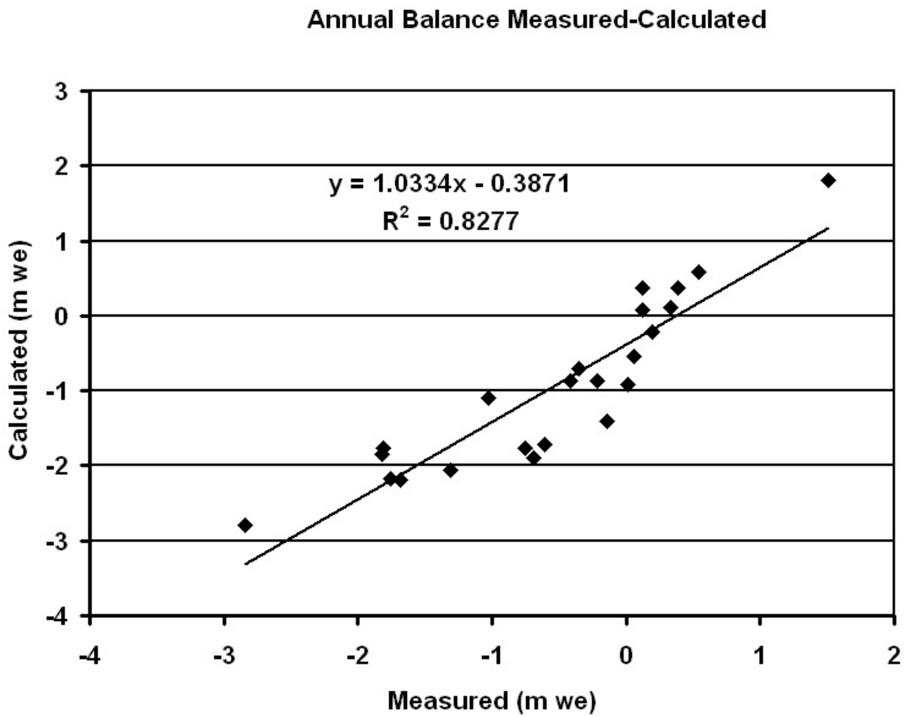

Fig. 7. Scatter plot of calculated versus measured annual balance on North cascade glaciers 1984–2005. Mass balance calculated using equations from Figs. 5 and 6.

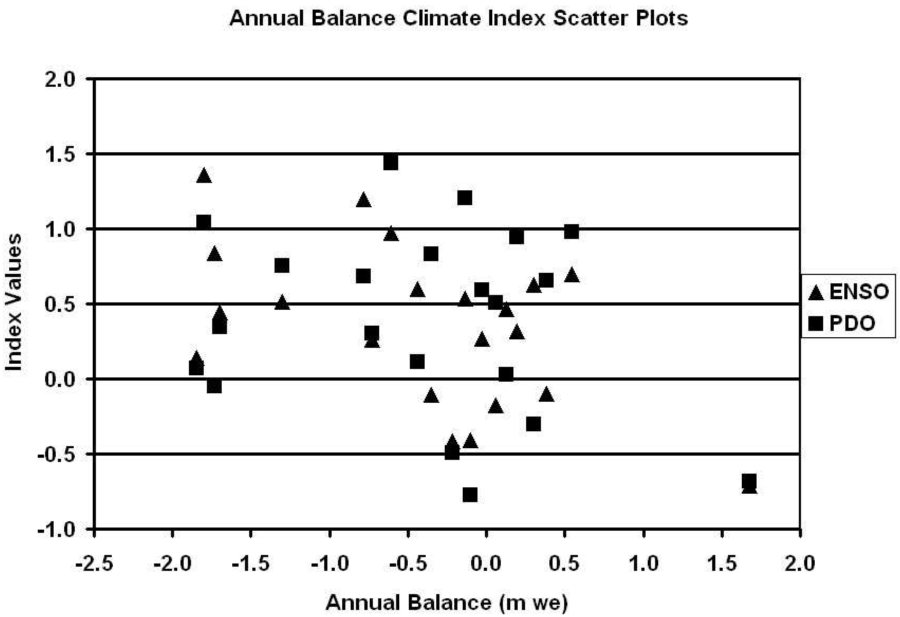

Fig. 8. Scatter plot for annual values of PDO (Mantua and others, 1997), ENSO (Wolter and Timlin, 1998). The poor fit of each index is evident. This prompted both combining the indices, but also looking at forecasting which demands less precision.

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Glacier balance measurement, forecasting
M. S. Pelto